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Stereo at the speed of light: high-speed digital stereo imaging at up to 100 million frames per second

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ABSTRACT

When shutter speeds approach a nanosecond you set your experiment up using a tape measure. Light-in-Flight imaging takes over when the length of the pulse and the shutter time can relate to a distance of two or three meters. This paper addresses the development of next generation ultrahigh speed digital imaging system and their application to stereo photography of ballistic, penetration, fragmentation, and spray events. Applications of high speed imaging from 1000 to 100 million frames per second are discussed along with the software used to evaluate various experimental methods. Applications range from ultra-high resolution still imaging using a laser strobe to laser illuminated digital movies.

Keywords: ballistic, impact, terminal ballistics, 3D imaging, crack propagation, stereo, laser photography, high speed photography, million frame per second, CCD, multi-pulse laser.

INTRODUCTION

While performing initial acceptance trials for new high-speed digital imaging systems it became apparent that in the process of evaluating two cameras we were generating stereo pair. Initial experiments indicated that the resulting 3D images provided almost as much insight into the ballistic experiments being performed as had our previous work in ballistic holography. As we developed each new high-speed sensor, we captured data in parallel. This has allowed us to begin an evaluation of digital stereo imaging as an engineering tool. From this initial work we demonstrated the integration of light sources, ultra-high resolution and ultra-high speed digital imagers, analysis software and display technology to fully utilize this new capability.

EXPERIMENTAL METHOD AND FACILITY

The Terminal Effects Laser Camera Center (TELCC) is a terminal ballistics research and evaluation facility at Bldg. 410 Eglin AFB, Florida. This facility was developed by Air Force Research Laboratory personnel to support development of several generations of holographic and high-speed electronic imaging systems. The facility is being transitioned for operational support to the Joint Munitions Test Project (Chicken Little). It is comprised of two gun tunnels with instrumentation bays adjacent to the launch and impact areas. Projectiles are launched from powder or air guns into targets of interest. The facility has capabilities to support several sets of digital cameras utilizing two imaging ports with armored glass windows to protect the optics. Timing is provided by sets of infrared light emitting diode screens that generate projectile velocity. Precision counters and pulse generators from Cordin and Stanford Research are utilized to generate the delays necessary to trigger the cameras and light sources exactly when the projectile is in the field of view. In most facilities the flash from impact or energetic materials reacting overpowers the camera resulting in poor image quality or saturated images. We have developed and perfected the use of Laser photography to overcome incandescence of object and impact flash. By use of 3 to 10 nanometer narrow-bandwidth laser interference filters combined with fast shutter mechanisms we have been able to reject most of the undesirable light. Both projectiles and fragments can be launched at various velocities and caliber's up to 40mm.

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An integrated, high-speed photographic system combining a high-repetition rate, pulsed ruby laser and high-framing rate CCD cameras has been demonstrated. Individually, the laser and cameras have been discussed previously and each was developed under the Small Business Innovative Research (SBIR) sponsorship through the Air Force Research Lab (AFRL). This paper presents for the first time dynamic digital stereo images captured at up to 1 MHz using the two elements integrated as a high-speed photographic system.

The laser and camera were integrated with the range master control clock, completing the high-speed, laser-based image acquisition system. The Bay-10 gun range at Eglin Air Force Base has the capacity for firing 30 mm rounds at up to 3,200 ft/s (e.g., A10 cannon).

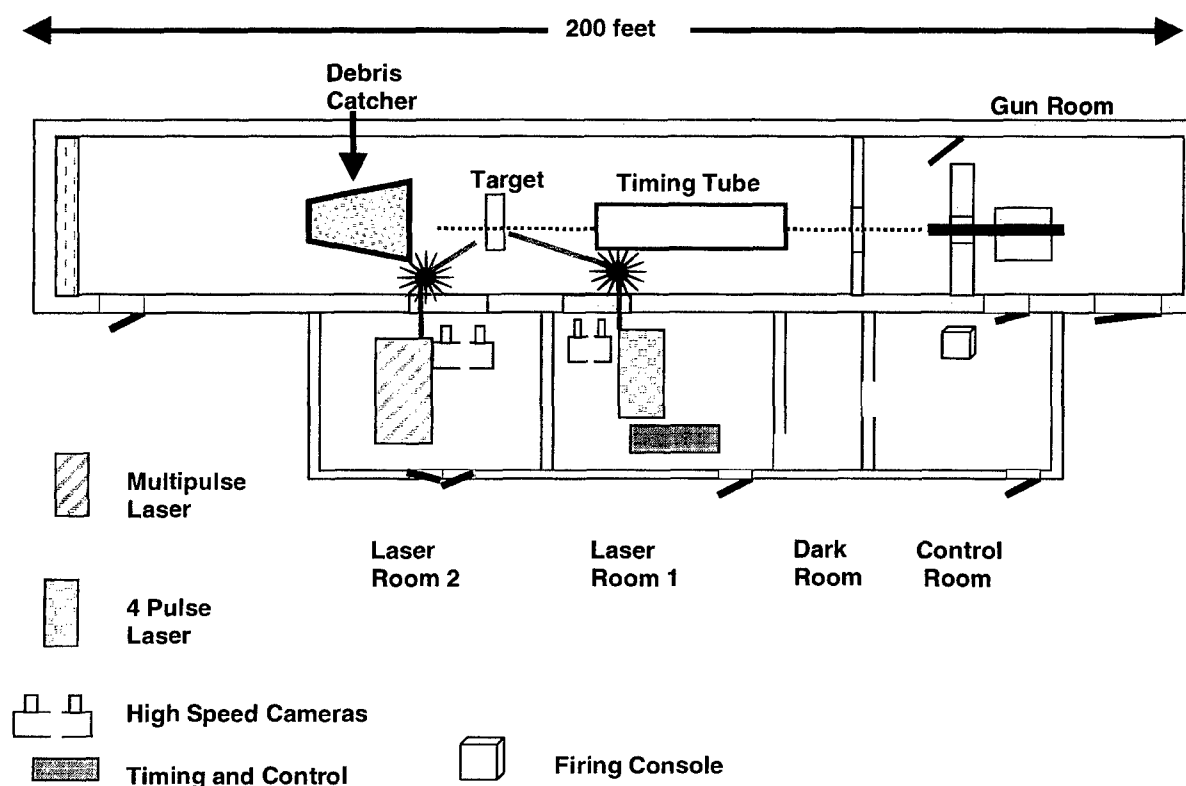


Figure 1. Terminal Effects Laser Camera Center at Interior Ballistics Facility Bay 10.

CAMERAS

The initial cameras used in our investigation were the Silicon Mountain Design (SMD) Mach1- 1000 frame per second -512 by 512 digital camera. For still imaging we used the SMD/Dalsa 4M4 - 2K by 2K focal plane sensors with 12 bit sensitivity. Soon after our initial experiments we developed a technique using an image mask over the charge coupled device chip to generate a 256 by 256 pixel -1 million frame per second digital camera. Images are stored under a mask so that shifting image down by one row hides the previous image. Up to 68 images on a 2K by 2K-focal plane sensor are possible. The original camera was not image intensifier shuttered (ungated). This sensor resulted in the prototype million frame per second camera, the SMD/Dalsa 64K1M. To further stop motion blur and permit outdoor operation we then developed a high-resolution image intensifier (GEN IV) and demonstrated shutter times down to 3 nanoseconds. Light from the laser moves at about 1- foot per nanosecond. For the highest speed ballistic events, 10 kilometer per second or 10mm/microsecond, a small object only moves 0.1 millimeters in a 10-nanosecond exposure time. This combination of fast shuttering using image

intensifiers and fast strobe flash using laser illumination stops all motion blur. We found that we also needed to diffuse the light to prevent noise from speckle. In various experiments we tried ground glass, tissue paper, and finally to our amazement a holographic diffuser from Physical Optics Corporation that almost completely diffused the beam with little attenuation.

For documentation of the various ballistic experiments, prototype Mach1-1000fps digital 10bit cameras and 64K1M million frame per second digital cameras were used with flood lights and the laser illumination system respectively. For high resolution still imagery, SMD 4M4 un-intensified 4 million pixel digital cameras and SMD/Videoscope million pixel digital cameras with a 3 nanosecond image intensifier shutter were used to capture data. These were mounted on crossbars and adjustable pan and tilt heads to provide for the desired stereo base separation and alignment.

The ultrahigh speed cameras were the prototype un-gated 64K1M Silicon Mountain Design (SMD) cameras with 17 frames of data. Sixteen of the frames are normally used for data and one for the active or open frame. With normal illumination this frame is open during readout and integrates ambient light until the mechanical shutter closes. With laser strobe this 17th frame becomes useful for data, or in a number of configurations a final still frame with multi-exposure from laser pulses. It is possible to configure the test so that the 16 initial frames each record a pulse with up to 10 or so multi-strobed images layering in the last image. This has been used for particle imaging velocimetry applications and to determine the rate of expansion of debris cloud volume growth when the particles are sub-resolved. The camera puts out a pulse train corresponding to the integration time for each image. The timing relative to synch pulse input is approximately 150 to 200 nanoseconds delay for the first frame. The integration time varies somewhat with frame rate, from 600 nanoseconds per frame at 1 microsecond interframe rate (1Mfps) to 8.8 microseconds at 10 microsecond interframe rates (100Kfps)

The imaging sensor in the prototype 64K1M is based on the Thomson CSF-type 7887 Frame Transfer CCD. The basic CCD is a 1K by 1K frame transfer array with custom timing and a metallic aperture mask applied by SMD to define the active pixels and storage registers. For 17 frames in active optical operation this results in approximately 61680 effective pixels for 248 by 248 pixel resolution. With this resolution the straight-line spacing would be 17 pixels or 238 microns for a rectangular sample arrangement. To maximize resolution, the pixel aperture mask openings are staggered to provide a 4 pixel maximum separation between active pixels. With 14-micron pixels, the aperture provides for a 9.5 (+/- 1) micron openings to help minimize cross-talk with the high laser illumination levels. With the staggered mask approach the resulting "pitch" is 56 microns between pixels. The 12 bit dynamic range and high sensitivity of the camera electronics significantly improves imaging performance and helps compensate for the "loss" of active area. A stair-step pattern of the CCD mask is implemented so that every 16 pixels horizontally and 17 pixels vertically starts a new subarray. The stair-step approach results in a pitch of image from the offset in the sampling spacing of pixels to maximize resolution. Due to the stagger, the resulting image has a roll of 14 degrees in the output image. This is compensated in the test set up with a mechanical wedge in the camera mount. The camera uses an imaging technology frame grabber in a standard personal computer and operates using SMD IMAPTM software. The resulting 12 bit files can be viewed a composite sheet as the figures in the paper, a movie file, or individual 12 bit TIF format files. Provision was also made to convert the 12 bit images into scaled 8 bit TIF format files. The camera integration time is user generated by even microsecond intervals resulting in frame rates of 1M, 500K, 333K, 250K, 200K, 166K, 142K, 125K, 111K, 100K, and slower by 1/M microsecond rate. The delay for the last frame is set to prevent premature readout while experiment generated light is present that would result in smear. Provision for a liquid crystal or mechanical shutter has been incorporated in the prototype while image converter shutters have been implemented in the final ULTRA series of cameras.

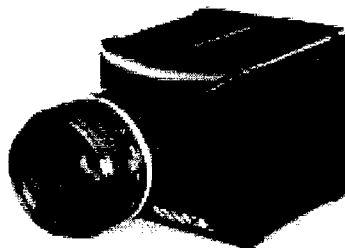


Figure 2. SMD64k1M Million Frame per Second Camera

Imager Format	256 x 256 x 17 frames monochrome
Dynamic range	12 bits
Pixel cell size	56 μm x 56 μm
Sensitivity	8 $\mu\text{V/e}$
Size	3.9" L x 3.7" W x 3.7" H
Operating Temperature	0 – 45 ° C
Weight	850 gm
S/N Ratio	70 dB
Power consumption	20 W
Dark current	~ 8 nA/cm ²
Lens mount	C or F mount
Frame rates	1M, 500K, 333K, 250K, 200K, 166K, 142K, 125K, 111K, 100K, and slower by 1/M microsecond rate
Readout rate	Up to 60 image sequences per second

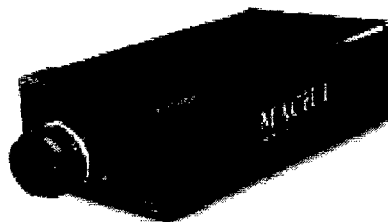


Figure 3. Mach 1 Camera, 512 by 512 pixel 1000 frames per second, 10 bit dynamic range, 1024 frames storage.

An integrated, high-speed photographic system combining a high-repetition rate, pulsed ruby laser and high-framing rate CCD cameras has been demonstrated. Individually, the laser and camera have been discussed previously and each was developed under the Small Business Innovative Research (SBIR) sponsorship through the Air Force Research Lab (AFRL). This paper presents for the first time dynamic digital stereo images captured at up to 1MHz using the two elements integrated as a high-speed photographic system.

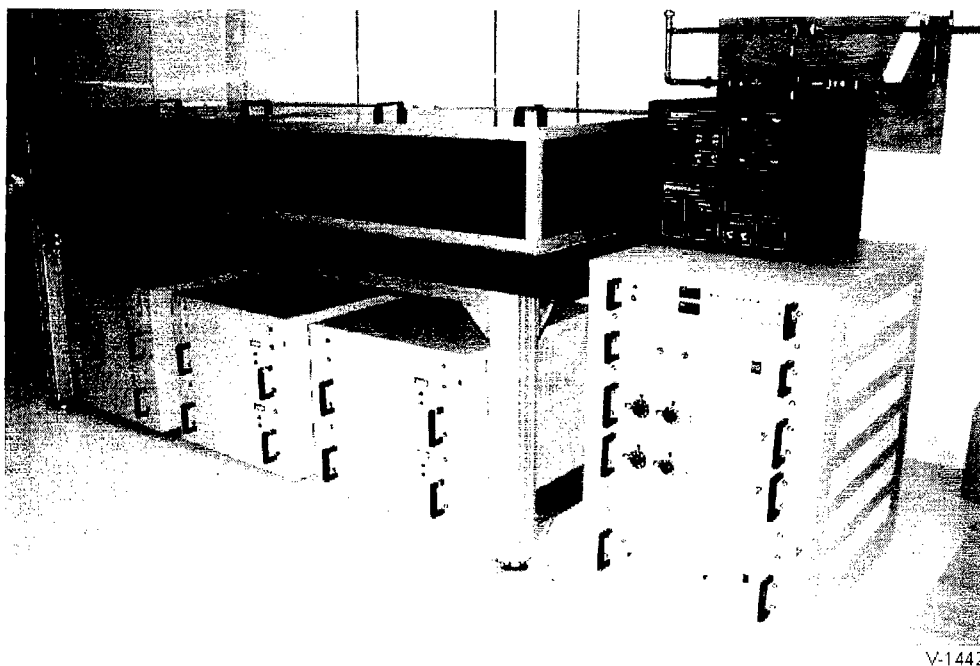
The laser and camera were integrated with the range master control clock, completing the high-speed, laser-based image acquisition system. The Bay-10 gun range at Eglin Air Force Base has the capacity for firing 30 mm round at up to 3,200 ft/s (e.g., A10 cannon). The tests presented in this paper were conducted using NATO 7.62mm rounds at approximately 800 m/s.

ILLUMINATION

Two lasers with a 694.3-nanometer output are used for illuminating the experiments. The first is a Lumonics HLS-4 flash lamp pumped ruby laser with peak output of 10 Joules. This system was developed for holographic applications and has capability to deliver up to 4 pulses in an 800-microsecond period. The nominal pulse width for this system is 15 nanoseconds. This system is used for high resolution still photography with the unshuttered SMD/DALSA 4M4 - 4 million pixels cameras, the SMD/Videoscope 1K by 1K pixel- 3 nanosecond cameras, and for use with the new HADLAND/IMCO ILS-4 10 nanosecond camera. Single pulses or multiple flashes per exposure are used to capture a blur free image/sequence of images.

For motion capture a two stage amplification repetitively Q-switched ruby laser was developed by Physical Sciences Inc. (PSI) in partnership with Continuum Electro-Optics Inc. under the Small Business Innovative Research program with the Air Force Research Laboratory (AFRL/MNMF). The oscillator stage incorporates the multiple Q-switching technology intracavity allowing for series addition of amplification stages. The current version of this laser uses two amplification stages and a novel pulse former to maintain pulse to pulse energy stability within the macropulse envelope.

The laser is capable of generating a train of 68 pulses at 500 kHz operation with micropulse energy of ~350 mJ each (>25 J for the macropulse). The test reported herein required less than 50% of this capability or ~100 mJ per pulse. The laser was



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Figure 4. Physical Sciences/Continuum Inc. 1 Million PPS Laser Illuminator System

selected as the master time control because the laser pulse could be located in time with high precision (<1 ns jitter) relative to a secondary laser output trigger. The laser pulse occurred at the end of the Q-switch open time, as previously shown by the authors. Recent advances in the camera trigger system allowed precise synchronization of the laser pulse and camera open shutter time. Data are presented showing this synchronization.

Q-switching of a laser cavity is normally done once to obtain a single giant pulse. This is usually done near the end of the flashlamp pump when the population inversion in the rod is at its highest. To obtain multiple pulses, the laser cavity is repetitively Q-switched over a period of time for which the gain is greater than the losses associated with the laser cavity. It

has been found that the laser cavity can be repetitively Q-switched with resulting pulses formed, for approximately the same duration in which the laser will emit when free running.

Typical applications for high speed imaging systems require large area illumination, on the order of 1000 cm^2 . Diffusers are also incorporated to remove laser speckle from the image. A low power negative lens and ground glass diffuser were incorporated into the optical train as shown in the following figure. Here the beam exiting the laser room has approximately a 1" diameter. The resulting illumination area on the target is on the order of 2500 cm^2 . Most exposures were acquired with a target to camera distance of about 4 meters. Tokina 35mm (150 to 500mm) zoom lens (f5.6/f32) were used on the cameras. Field of view varied from 250 mm to 75 mm. Most exposures were made at f/11 to f/16. Provision for filtering ambient light with ruby laser line filters and neutral density filters from Andover Optics was made. The ruby line filters were also used to reject light from the impact flash during tests with metal objects. Speckle was controlled using lens tissue sandwiched between two layers of 3 mm thick ground glass. Later tests made use of a holographic polymer diffusers from Physical Optics Corporation. A much higher light transmission (over 90%) was obtained by use of the thin polymer.

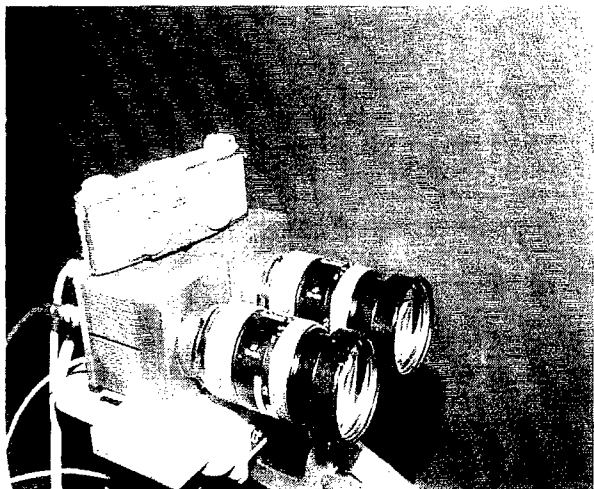
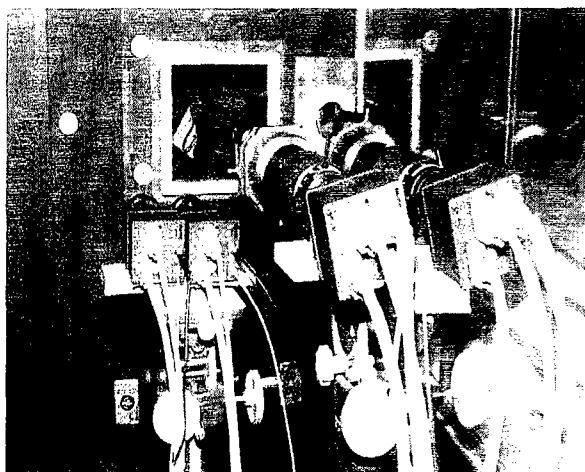
SOFTWARE

Various software is used in the generation and analysis of the stereo images. IMAP is the native package that is used on the SMD/Dalsa data acquisition system to capture and store the image in native 12 bit, 8 bit, or 16 bit files. For the movie sequences IMAP provides the ability to create a sequence of individual TIF or BMP files from the raw image. IMAP has dynamic range mapping, flat field correction, and some limited image processing. Adobe Photoshop or Image-Pro is then used to adjust each image, matching the image sizes for slight variations in rotation and focal length. From the corrected images stereo pair are produced in several formats using different commercial software applications. For simple anaglyph or .jps type images, 3D Stereo Image Factory Plus from SOFTreat is used as well as DEPTHCHARGE Developers Studio with 3D STUDIO MAX plug-ins from VREX. Platypus Animator from C Point Pty. Ltd., is used to create AVI or MPEG files from the resulting anaglyph image sequences. NEOTEK has provided a useful measurement program as a part of their 3D imaging and analysis suite. The KnowledgeVision Composer and Presenter package has integrated a 3D cursor for X,Y, and Z measurements of the position of an item while being displayed in stereo using liquid crystal shutter. Advanced software packages that are being evaluated to photogrammetrically correct and measure items in the image pairs are FotoG-FMS from Vexcel Corporation, PhotoModeler 3.1 from EOS Systems Inc., and Shapecapture 3.1 from Shapequest, Inc. In addition to making measurement of the position of items, these software applications are used to create 3D CAD models. These generate solid models in wire-frame or bitmapped 3D for export into Autocad or other engineering applications. The key intent to translate the velocity, position, and shape from the imagery data into the frame of reference for the modeling and simulation engineering CAD tools that the analyst is using.

For the measurement of particle motion in stereo, Flowmap Stereo from DANTEC, Inc. is being evaluated. This software is designed to import laser strobed stereo images for Particle Imaging Velocimetry. Instead of typical planar PIV for two-dimensional flow, Flowmap provides true 3-vector information on the direction of each particle.

DISPLAY

Data are displayed on Viewsonics 21-inch color monitors (P815) using customized shutter glass emitters from Stercographics and from Neotek. Crystal Eyes, Neotek, and VRex liquid crystal glasses are used to view the data in 3D for presentation and analysis. Often for viewing and for group presentation anaglyph glasses (Red-left and Blue-right lenses) are used and provide satisfactory results. A few of the more art-like images (Edgerton ballistic photo reproductions) have been converted over to hardcopy in 3D courtesy of San Francisco Imaging, Inc. using the Stereo Jet polarized laminate process. This has provided interest results for both permanent hardcopy display and projection using overhead projectors and silvered projection screens.



Clockwise:

Figure 5. High Resolution 4 Million Pixel Stereo Pair and Million Frame Per Second Stereo Pair.

Figure 6. Laser Interference Narrow Band Filters for rejection of ambient and experiment generated flash.

Figure 7. 1950's Stereo Realist Camera and 4 Million Pixel Digital Stereo System

Figure 8. 3 Nanosecond Image Intensified 2K by 2K Pixel prototype camera for light in flight experiments

IMAGES

The first images shown below are from field experiments with the 1000 frame per second digital camera system. Two systems were mounted on a common platform and used for evaluation of stereo imaging in the field. A water tank experiment with plexiglass windows was designed to observe projectile penetration and pressure deformation due to generated shockwaves. The second set of images are from an experiment with a professional golf instructor striking a ball into a plexiglass shield in front of the cameras. This experiment used two different configuration cameras and the diffculting in converging the images is a result of slightly different scale factors for the CCD image sensor and excessive toe-in. The third set of images are from a 7.62 mm projectile at 2800 feet per second. This image pair is extracted from the movie captured at 1 Million frames per second with the SMD 64K1M unintensified camera. The PSI multipulse laser was used to frame the images and prevent blur during the 1 microsecond integration time. The 10 nanosecond laser pulse prevents any

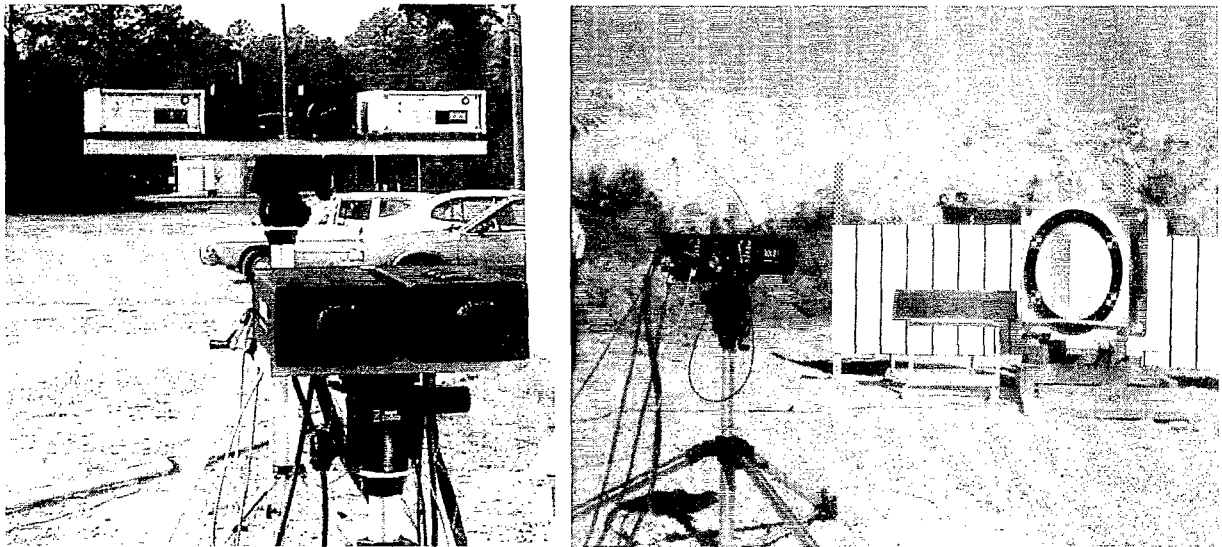


Figure 9 and 10. Range configuration for 1000 frame per second and million frame per second stereo experiments.

motion from being detected while the sensor is shifting from one frame to the next. The final image set is from a extremely high velocity impact using the gated 1K by 1K sensors. These images represents 3 nanosecond exposures of the fine cloud of aluminum particles resulting in a small pellet impacting a satellite skin. This experiment simulated micrometeorite impact on a satellite skin or the space station. No flash is noted in the image where normally the image would be totally saturated from the burning aluminum particles.

These images are set for viewing with a Stereoscope viewer such at those inexpensive ones available from Hubbard Scientific, P.O. Box 760, Chippewa Falls, WI, 54729. Reproduction may skew the scale factor. A high quality copier can shrink or enlarge the images until they adjust for the correct inter-pupillary distance.

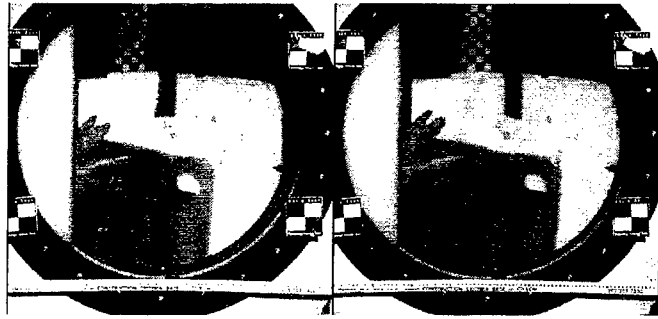


Figure 11. 1000 frame per second capture of projectile penetrating water tank at high velocity.

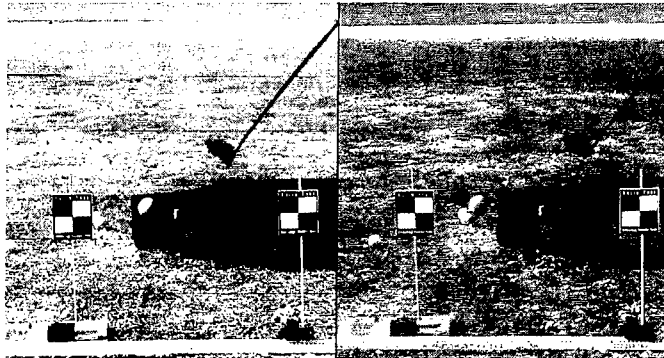


Figure 12. Experiment with two 1000 frame per second cameras and golf ball. Excessive toe-in and scale factor difference.



Figure 13. Million frame per second capture with laser photography of projectile penetration of target card.

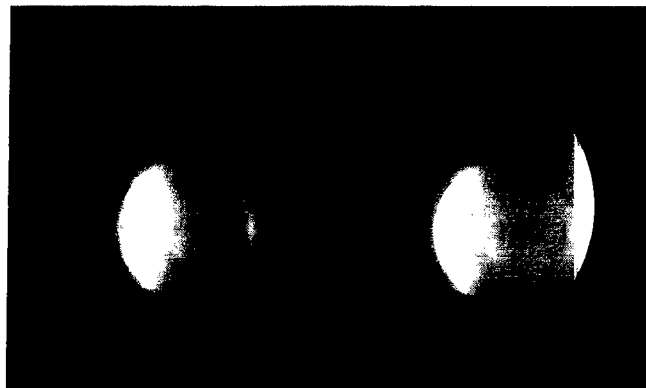


Figure 14. Hypervelocity Impact at several kilometers per second into aluminum sheathing. Note no impact flash.

NEW TECHNOLOGIES

Based on the prototype experiments and systems we are currently finishing development of a new series of cameras optimized for stereo laser photography. We have been jointly developing these systems with Dalsa/SMD; DRS Hadland/IMCO; and Atomic Weapons Establishment of the U.K.

The first system is the ILS-4. This system is comprised of a fast decay phosphor 40mm image intensifier (GEN II) coupled to a Dalsa 4M4 camera with a 2K by 2K sensor. Shutter times down to 10 nanoseconds are possible to freeze the fastest moving projectile. As in all the new cameras a viewfinder between the optical system and camera allows precise focus and alignment. This system is capable of accepting up to 63 triggers for multiple exposure of small particles crossing the field of view for PIV and debris tracking applications.

The second system is the ULTRA 17. With 17 frames and 512 by 512 pixel resolution this camera was designed to provide the resolution indicated from the earlier experiments with the SMD 64K1M. The same type of aperture mask is applied to a Thomson 7889 CCD to provide on chip storage. Limitations in the vertical-clocking rate for this CCD has limited the frame rate of the ULTRA 17 to 150,000 frames per second. This however is sufficient for most ballistic experiments where projectiles are moving at rates of 1 to 4 millimeters per microseconds.

The ULTRA 68 is capable of capturing 68 frames of data at 500,000 frames per second. The initial version of this sensor has a resolution of 256 by 256 pixels. A dual image intensifier configuration provides for shuttering down to 20 nanoseconds and amplifications for capturing images at this high rate. A unique beam-splitter arrangement projects the imaged field onto the face of the segmented photocathode of the intensifier. While half the CCD is being exposed the other half is being shifted, clearing space for new images. Very high burst rates in sequences of 4 images are possible.

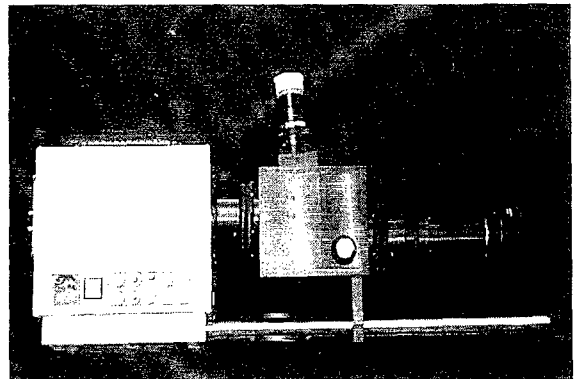
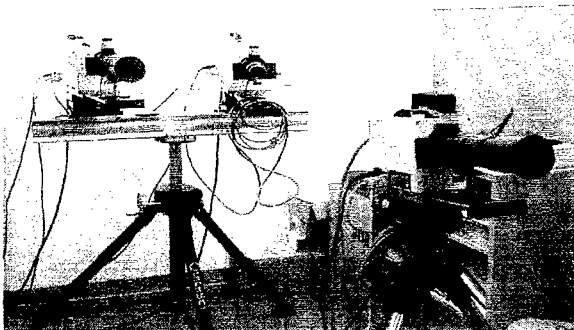


Figure 15 and 16. ULTRA 8 - 100 Million Frame Per Second Stereo System, ULTRA 17- 150,000 Frame Per Second Stereo System and ULTRA 68- 500,000 Frame Per Second 68 Frame System.

The ULTRA 8/ULTRA 8 STEREO was designed to provide the highest performance needed for ballistics or high energy physics. Up to 9 images at 600 by 600 pixel resolution can be captured on the large 2K by 2K charge coupled device sensor at rates up to 100 Million Frames per Second. The two stage 40mm image intensifier provides fast shuttering down to 20 nanoseconds and amplification for capturing data with the short pulses from the laser. As shown two Ultra 8 cameras are mounted on a positioning system with precision tilt, yaw, roll and stereo base separation. The entire system is mounted on a heavy duty Quik-Set tripod with geared head for field use. Through the lens focusing is accomplished with the viewfinder and two slots are available in front of the sensor for neutral density and laser interference filters. The current design for all sensors includes direct connect to a PC controller via frame grabber or with a fiber interface board for remote operation.

We also are beginning development of a single 7K by 4K CCD sensor for macro-still laser photography using a range-finder type beamsplitter. This camera will have a single Pentax medium format aperture with image splitting prisms, turning mirrors, and objective lenses. This system is in final design and will be reported in subsequent proceedings.

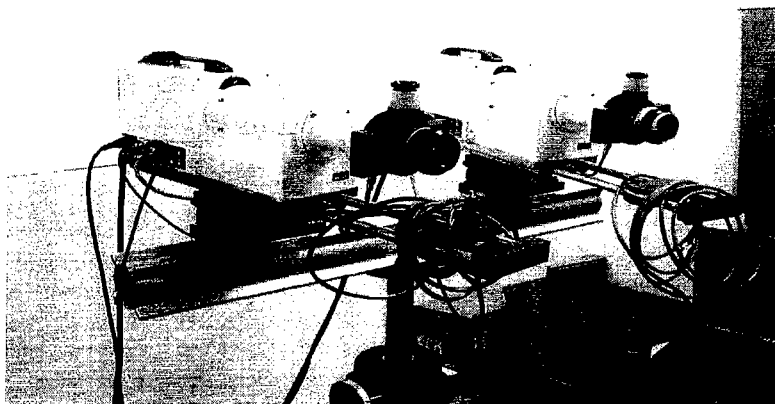


Figure 17. ULTRA 8 100 Million frame per second Stereo system with crossbar and precision attitude adjustment system.

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